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1.—TERTIARY THOLEIITE MAGMA IN WESTERN AUSTRALIA.

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INTRODUCTION.

Subsequent to a description of the tholeiitic basalts of Cape Gosselin (10) Professor E. de C. Clarke and Dr. Dorothy Carroll kindly placed at my disposal specimens of Tertiary basalts from all the other known localities in the south-west of Western Australia, viz. from Bunbury [1686], from Gelorup, about 5 miles south of Bunbury [16263], from the Capel River [1 195], and from the mouth of the Donnelly River [4342]. The localities are shown in Figure 1. These are all varieties of theoleiite more or less similar to the Cape Gosselin tholeiites. A further specimen [4496], said to come from Bridgetown, but of doubtful locality (probably Darradup) is also a typical tholeiite. Chemical analyses of the Bunbury and Donnelly River tholeiites were made in the Geology Department, University of Melbourne, by permission of Professor Skeats. The analyses and the mineralogical compositions of these rocks make it clear that they are fairly typical plateau basalts.

THE TERM "THOLEIITE."

It is well at this stage to state what is meant by the term "tholeiite." As employed by Rosenbusch (19, p. 427) and by Holmes (15, p. 225) tholeiite indicates a basaltic rock showing intersertal texture, and free from olivine, consisting essentially of calcic plagioclase, pyroxene and iron-ores, the interstices being occupied by a mesostasis of glass, globulitic glass, or devitrification products. Olivine-bearing types were distinguished as olivine-tholeiites. Tyrrell (21, p. 240) expanded the term to include similar rocks which carry phenocrysts of plagioclase approaching anorthite in composition; and Holmes and Harwood (16, p. 9) adopted this wider sense when classifying the various types of tholeiite dykes in the north of England.

More recently, however, Kennedy (17, 18) has suggested that the significance of the tholeiites lies in their distinctive chemical and mineralogical characteristics, and in their petrographic association, rather than in their intersertal texture. In the light of his work a *tholeiite* may be defined as a basaltic rock containing little or no olivine, basic plagioclase, lime-poor pyroxenes (pigeonites) and iron ores, in a mesostasis of glass; and giving rise to an acid quartzo-felspathic residuum. They are thus quite distinct from the *olivine-basalts* which contain abundant olivine, basic plagioclase, and lime-rich pyroxenes (diopsidic augites), and give rise to an alkaline, quartz-free residuum. The emphasis of the distinction is thus placed on the types of pyroxene which characterise the rocks, and the character of their subsequent differentiates. These two widespread types of basalt are regarded by Kennedy as corresponding to two types of primary basalt magma (18) whose chemical composition are as follows:—

	Olivine-basalt Magma type.	Tholeiite Magma type.
SiO_2	45	50
Al_2O_3	15	13
$Fe_2O_3.FeO$	13	13
MgO	8	5
CaO	9	10
Na_2O	2·5	2·8
K_2O	0·5	1·2

The acid differentiates of the olivine-basalts are trachyandesites, trachytes and phonolites; those of the tholeiites are quartz-dolerites, andesites and rhyolites.

This is to make the rock type "tholeiite" practically synonymous with that of "plateau basalt," introduced by Washington (24). The textural significance of the term tholeiite is conveyed with equal adequacy by the terms "mero-crystalline" and "mesostasis." If it is to be retained in this, its original, sense, it should be used only as an adjective, "tholeiitic," and not as a rock name, because such a texture is dependent on the local rate of cooling, so that a single flow commonly shows at one place basaltic (intergranular, doleritic, or ophitic) texture, and at another tholeiitic texture. Thus the Whin Sill, while normally a quartz-dolerite, is marginally tholeiitic. Moreover, the indiscriminate use of the name tholeiite in connection with olivine-basalts (cone-basalts of Washington (24)), and plateau basalts, is liable to introduce a false sense of similarity.

If, on the other hand, as Kennedy indicates, the rocks originally termed tholeiites because of their intersertal texture, also possess a characteristic chemical and mineralogical composition, and a distinctive petrographic association, it seems desirable to broaden the definition to include these features, thus constituting tholeiites as a definite type of plateau basalt.

The Western Australian rocks to be described qualify for the use of the term, whichever meaning is attached to it.

THE WESTERN AUSTRALIAN THOLEIITES.

1. *The Bunbury Tholeiite.*

The outcrop of tholeiite at Bunbury, about 90 miles south of Perth, has been mapped and described by Saint Smith (20, p. 15). His map was based on an earlier one by Gibb Maitland (Ann. Progress Report, Geol. Survey W. Aust., 1897). Much additional information has been accumulated by the Public Works Department in Perth, and this was kindly placed at Professor Clarke's disposal by Mr. Stevenson Young, of the Harbours and Rivers Department, and Mr. Hutchinson of the Water Supply Department. The accompanying geological map (Fig. 2) and sections (Fig. 3) were compiled by Dr. Carroll from bore records and data obtained from large scale maps of the Public Works Department, W.A.

The tholeiite outcrops at sea level as a nearly horizontal flow, stretching southwards along the western coast for about a mile from the Breakwater at Point Casuarina. The surface of the lava rises slightly towards the south, and the bore records indicate that the flow dips towards the east (Fig. 3). The outcrop is in part a wave-cut platform, in which the sea has eroded channels, but there are more elevated parts which appear to be remains of old sea cliffs, and are now covered by sand dunes. Along the coast the tholeiite shows strong vertical columnar jointing, the columns being rudely pentagonal in cross section and averaging about 15 inches in diameter. Some portions weather much more readily than others, suggesting a possible variation in composition or texture. The Breakwater itself is built on the reef formed by the western edge of the tholeiite flow, which extends beneath Koombana Bay, at a depth of 20-35 feet below low-water mark. It is covered by sands and clays, and has an irregular surface, since probing (records) revealed "pockets" containing clay and plant remains.

The flow continues under the township of Bunbury, beneath a cover of sands and clays, as far east as the railway line, where, although there is no surface feature to indicate a change, the bore records show several hundreds of feet of sediments (Section CD, Fig. 3). The most easterly bore again strikes the tholeiite at 46 feet below the surface (Figs. 2, 3), as do those on the northern shore of the Leschenault Estuary. The geological section suggests that there is here an old in-filled valley which had walls of lava, indicating either intense local erosion of the flow, or trough faulting, subsequent to its extrusion. A third possibility is that there is more than one lava flow present, but this does not explain the continuity along the section AB (Fig. 3), or the steep edges of the lava indicated by the bores along the Section CD (Fig. 3). Recent elevation has not been sufficient for erosion to expose the greater part of the tholeiite.

The variable thickness of the flow, from 50 to 97 feet, and its occurrence at different heights above sea-level suggest that it was extruded on an old land surface. In places it overlies a red clay, below which are water-bearing sands and gravels.

At Gelorup tholeiite outcrops at 25-30 feet above sea-level, and at Capel (not shown in Fig. 3) a similar lava outcrops at 52 feet above sea-level, indicating that the pre-basaltic land surface was irregular.

The flow is of Tertiary age, and was regarded by the late Professor Edgeworth David as Upper Pliocene (8, p. 87). In some localities it is overlain by the Coastal Limestone Series, which is of Late Tertiary or Recent age. It probably extends to the east and south of Bunbury, but this could be proved only by boring.

The Bunbury tholeiite is a handsome rock, consisting of abundant large columnar phenocrysts of plagioclase set in a dense blackish groundmass. It breaks with an uneven fracture, and is an excellent roadmetal, for which purpose it is quarried. In thin section the large felspar phenocrysts, which may be as large as 10 mm. by 3 mm., are found to consist of a broadly twinned bytownite (Ab_{25}), with a maximum extinction angle in the symmetrical zone, perpendicular to (001) (010), of 38°-39°, following Goransen's data (14). (Note:—The plagioclase phenocrysts in the Cape Gosselin tholeiites (10) given as Ab_{35}, using Idding's diagram (Rock Minerals, p. 228), are also truly bytownites of Ab_{25}.) Some show zoning, the peripheral zones being somewhat more sodic (Ab_{45}): and frequently they are glomero-porphyritic. The plagioclase phenocrysts are set in a mero-crystalline, intergranular groundmass, consisting of plagioclase laths, granular pyroxenes, and a variety of glasses—black, green, and yellow. The plagioclase is labradorite about Ab_{45}: but the individual pyroxenes are too small for their composition to be determined by the optical methods available. The yellow and green glasses grade in colour into one another, and are fibrous from devitrification. They probably differ only in the state of oxidation of their iron content. The black glass is seen, under high magnification, to consist of similar material which contains innumerable globulites and skeletal crystals of iron ore, and represents glass in which the iron oxides had concentrated preparatory to crystallizing out. Small patches of chloritic material, coarser in grain than the groundmass, suggest the previous existence of small microphenocrysts of a ferromagnesian mineral—augite, or possibly olivine.

An analysis of this rock is given in Table I., and is discussed in a subsequent section.

2. *Gelorup Tholeiite.*

A similar basalt [16263] occurs near Gelorup, about 5 miles south of Bunbury on the Capel road. The outcrop, which has been quarried for road metal, is about a mile east of the road (Fig. 2). It is surrounded by thick timber, and to the west there are high sand hills which were at one time sand dunes. The line of high ground runs for some distance north and south, suggesting that the outcrop is only part of a more extensive lava flow.

It is dark grey, crystalline rock, studded with irregular mega-phenocrysts of plagioclase, as large as 0.5 cm. in diameter. Under the microscope it is seen to be a tholeiite, with phenocrysts of basic plagioclase (Ab_{25}) set in a groundmass of plagioclase laths, (Ab_{40-45}), and pyroxene, with a mesostasis of black glass, containing innumerable minute skeletal crystals of iron ore. Patches of green, brown, and yellow-brown glassy material occur throughout the rock, filling small vesicles, and sometimes surrounded by minute columnar growths of pyroxene. The plagioclase phenocrysts show broad lamellar twinning, and are sometimes zoned. Frequently they are segregated into clots along with granular crystals of pyroxene.

Two varieties of pyroxene are present. One is a pigeonite ($2V = 0°-5°$) and optically positive, with relatively low birefringence. The other is a brightly polarizing variety, biaxial, with a fairly large 2V, a birefringence about 0.03, and a relatively high refractive index. It somewhat resembles olivine in appearance, but has a good cleavage, and is probably diopsidic.

3. *Capel River Tholeiite.*

Specimen [16195] is from an outcrop of basalt in the bed of the Capel River, about six miles east of the township of Capel. It is a dark grey, slightly vesicular rock, studded with yellowish phenocrysts of glassy plagioclase, often in small clots.

In thin section it is a typical tholeiite, closely comparable with those from Bunbury and Gelorup. The plagioclase phenocrysts show broad lamellar twinning and strong zoning. The cores of the crystals show a maximum symmetrical extinction of about 38°, corresponding to a composition of Ab_{25}. The outer zones approach basic andesine in composition. They are set in a merocrystalline groundmass of plagioclase laths (Ab_{45}), intergranular to sub-ophitic pyroxene, and a mesostasis of globulitic iron-rich glass. Much of the pyroxene is almost uniaxial pigeonite, with 2V between 0°–5°, with a positive sign. The optic axial angle appears somewhat higher in some instances (about 45°), indicating that there are two types of pyroxene present, presumably a magnesia-rich pigeonite, and a more lime-rich pigeonite. The glassy mesostasis consists of colourless glass crowded with globulites and skeletal crystals of iron ore. Patches of green and orange-yellow glassy material occur throughout the rock, frequently lining small vesicles.

4. *The Donnolly River Tholeiite.*

Outcrops of tholeiite occur at the mouth of the Donnelly River, in the extreme south-west of Western Australia, and a little further inland, three miles north of Silver Mount and one mile south of the junction of Fly Creek with the Donnelly River. The outcrops are shown on H. P. Woodward's map of this part of Western Australia (25).

Gibb Maitland (11, pp. 13-15) records the presence of basalt, at depth, along the Warren River, about 13 miles to the west of the Donnelly River. According to the bore records there are two flows of basalt, 20 to 40 feet thick, intercalated with sands and lignites, and overlying coral limestone, and a fossiliferous sandstone containing saurian remains. Woodward, however, casts doubt on the reliability of the bore records (24), because only an incomplete suite of specimens of the cores were submitted to the Geological Survey, and these did not include any basalts.

The Donnelly River tholeiite resembles that from Bunbury. It is a dark greyish, finely crystalline rock, studded with tabular phenocrysts of glassy plagioclase, which may be as large as 10 mm. by 5 mm., and are frequently glomero-porphyritic. These show broad lamellar twinning, and sometimes zoning. The cores consist of bytownite (Ab_{25}), while the outer zones are more sodic (Ab_{45} about). The groundmass in which these phenocrysts are set consists of laths of plagioclase (Ab_{45}), granular augite, laths of ilmenite, rare apatite rods, and a little devitrified green glass. The pyroxene crystals are too small to determine their composition optically by the means available. The rock is rather more crystalline than the Bunbury tholeiite, and is somewhat similar to the doleritic tholeiites of Cape Gosselin (10).

The outcrop north of Silver Mount is rather more glassy, and is finer grained: and in addition to the plagioclase phenocrysts, contains rare phenocrysts of augite (25).

An analysis of the Donnelly River tholeiite is given in Table 1, and is discussed in a subsequent section.

5. *The Darradup Tholeiite.*

A further outcrop of tholeiite occurs at Darradup, on the Blackwood River, about 30 miles north of Cape Gosselin. This is probably the locality of specimen No. 4496, labelled Bridgetown (which is some miles to the east, in gneiss country). Farquharson (25, p. 52) described the Darradup rock as a porphyritic doleritic basalt, with phenocrysts of basic plagioclase, set in a doleritic or subophitic groundmass of plagioclase, augite, and black areas containing much iron, with occasional, almost isotropic, green chloritic patches pseudomorphous after a ferromagnesian mineral.

This description fits Specimen No. 4496, which consists of phenocrysts of bytownite (Ab_{25}) set in a coarse merocrystalline to sub-ophitic groundmass of plagioclase laths (Ab_{45}), ophitically intergrown with a pigeonitic pyroxene ($2V = 40°$), and with abundant intersertal dark glass, the dark appearance of which is due to the presence of innumerable globules and skeletal crystals of iron oxide. The glassy matrix consists of devitrified yellow or green glass, and this occurs as clear patches. Occasional small green chloritic areas are obviously pseudomorphous after a ferromagnesian mineral, which may have been augite or olivine.

6. *The Cape Gosselin Tholeiites.*

These have been described previously (10). They resemble the various tholeiites just described except in their lack of megaphenocrysts of bytownite.

CHEMICAL ANALYSES.

In the following table the two new analyses are given together with that of the Cape Gosselin tholeiite. In addition, analyses of typical Salen, Brunton, and Talaidh types of tholeiite are appended for comparison.

TABLE I.

	1.	2.	3.	S.	B.	T.
SiO_2	49·46	50·57	51·14	50·41	50·07	51·28
Al_2O_3	14·74	15·11	14·56	15·14	14·53	14·83
Fe_2O_3	2·45	3·65	4·05	2·71	1·76	2·49
FeO	9·10	8·80	7·04	7·95	8·26	5·89
MgO	6·30	5·55	6·25	6·57	6·77	7·45
CaO	12·01	10·64	10·15	11·30	11·50	11·59
Na_2O	2·65	2·29	3·96	2·29	1·93	1·93
K_2O	0·55	0·57	0·58	0·82	0·85	0·66
H_2O+	0·13	0·25	0·54	1·01	0·82	0·91
H_2O-	1·40	1·42	1·35	0·72	0·52	1·41
CO_2	tr.	nil	0·05	0·07	1·61	0·45
TiO_2	1·48	1·37	0·01	1·30	1·14	0·87
P_2O_5	0·03	0·07	0·02	0·15	0·16	0·14
MnO	0·17	0·26	0·16	0·17	0·19	0·20
Cl	n.d.	n.d.	*Nil*	n.d.	tr.	n.d.
S	n.d.	n.d.	*Nil*	0·06	0·08	0·06
BaO	n.d.	n.d.	*Nil*	0·03	0·04	0·01
	100·48	100·55	99·86	100·80*	100·33†	100·24‡

* Etc. 0·05 † Etc. 0·10 ‡ Etc. 0·07

1. Tholeiite, Bunbury (No. 1686). Analyst, A. B. Edwards.
2. Tholeiite, Mouth of the Donnelly River (No. 4342). Analyst, A. B. Edwards.
3. Tholeiite, Cape Gosselin (No. 10353). Analyst, A. B. Edwards (10, p. 20.)

S. Olivine-tholeiite (Salen type), Kielderhead, Northumberland. Analyst, H. F. Harwood (16, p. 16).

B. Tholeiite (Brunton type), Bingfield Dyke, Redhouse Burn, Northumberland. Analyst, H. F. Harwood (16, p. 23).

T. Tholeiite (Talaidh type), Kielder Viaduct Dyke, Kielder Burn, Northumberland. Analyst, H. F. Harwood (16, p. 28).

Examination of Holmes and Harwood's study of the tholeiite dykes of the north of England (16) makes it clear that the West Australian tholeiites have close affinities with the Salen, Brunton, and Talaidh (pronounced Tala) type of English tholeiites, both chemically and mineralogically. The presence of phenocrysts and clots of basic plagioclase, bytownite in the West Australian rocks, is parallel to the common presence of bytownite-anorthite phenocrysts and clots in the English types. The occasional olivine in the Cape Gosselin tholeiites, and the presence in the Bunbury and Darradup rocks of pseudomorphs, possibly after subordinate olivine, indicate an affinity with the Salen type of tholeiite. The microtextures of the Australian tholeiites, moreover, are comparable with those of the Salen and Brunton types. The "sheaves and fan-shaped cervicorn groups of slender augite," characteristic of the Talaidh type, have not been observed.

In certain respects, however, the West Australian tholeiites differ from the English types. They are extremely deficient in phosphorus, and rather richer in total iron oxides and soda.

In Table II. the average of the three West Australian tholeiites is compared with Plateau Basalts (24) from several parts of the world.

TABLE II.

	1	2	3	4	5
SiO_2	50·39	50·61	47·60	48·79	50
Al_2O_3	14·80	13·58	12·76	11·96	13
Fe_2O_3	3·38	3·19	2·49	2·51 }	13
FeO	8·31	9·92	10·83	12·10 }	
MgO	6·03	5·46	5·79	5·60	5
CaO	10·93	9·45	10·71	10·15	10
Na_2O	2·93	2·60	2·15	2·40	2·8
K_2O	0·57	0·72	0·56	0·70	1·2
TiO_2	0·96	1·91	...	4·17	...
P_2O_5	0·04	0·39	...	0·37	...
MnO	0·20	0·16	...	0·21	...

1. Tholeiite of Western Australia (3 analyses).
2. Deccan Traps (11 analyses).
3. Faroe basalts (2 analyses).
4. Iceland basalt (1 analysis).
5. Non-porphyritic Central Magma-type of Mull.

It will be seen that the West Australian rocks, though similar, contain less phosphorus and titania, and rather less iron than the typical plateau basalts, and rather more alumina, lime, and magnesia.

Chemically, therefore, they are intermediate between these two closely related types—tholeiite and Plateau Basalt.

A SUGGESTED CLASSIFICATION.

Despite the close mineralogical and chemical similarity of the West Australian tholeiites so far described, they may be divided into two main groups:—

(1) Tholeiites of the *Bunbury type*, with megascopic phenocrysts of bytownite, and

(2) Tholeiites of the *Gosselin type*, in which microphenocrysts of bytownite are present, but megaphenocrysts are characteristically absent.

Further subdivision on the basis of the abundance or paucity of the glassy mesostasis does not seem to be warranted, since this feature is so closely related to local variations in the rate of cooling after extrusion within a single lava.

Using this classification, the Bunbury, Gelorup, Capel River, and Donnelly River tholeiites are of the Bunbury type, while the Cape Gosselin and Darradup rocks are of the Gosselin type.

THE EXTENT OF THE THOLEIITE MAGMA.

It is clear that the extreme S.W. part of Western Australia was intruded during Tertiary times by an extensive tholeiite magma. The volume and extent of the extrusions arising from this magma cannot be gauged from the meagre existing outcrops. Some of these are merely residuals of larger flows: others are uncovered portions of otherwise hidden flows of unknown size. Still other lavas are completely buried, and can only be discovered by deep boring. Further search wherever the underlying sedimentary series is exposed should reveal additional necks, dykes, or pipes, by which lava flows, now eroded, reached the surface. Gibb Maitland (13, p. 42) refers to the existence of such dykes.

It is possible, as he has suggested (13, p. 42), that the tholeiite magma was not confined to the S.W. corner of the State, but was much more widespread (Fig. 4). Examination of West Australian publications has revealed a number of recorded occurrences of lavas, dykes, and sills of tholeiitic character or affinity in various districts. Only rocks which were quite fresh and unmetamorphosed, and showed intrusive relations to all but Tertiary rocks, were considered. Tholeiitic types complying with these specifications have been recorded from Norseman (3) [lat. 32° 10′ S.: long. 121° 48′ E.], East Murchison (6) [lat. 26° 20′ S.: long. 115° 0′ E.], Yilgarn (2) [lat. 30° 40′ S.: long. 119° 0′ E.], Meekatharra (7) [lat. 26° 39′ S.: long. 118° 32′ E.], Yalgoo (4) [lat. 28° 23′ S.: long. 116° 40′ E.], and in the region between Laverton and the South Australian border (22) [lat. 28° 40′ S.: long. 122° 29′ E.], but their most extensive development is in the Lofty Ranges, and the drainage basin of the Ashburton River [lat. 22° 0′ S.: long. 115° 0′ E.], and in the Hamersley-Ophthalmia Plateau (23) [lat. 22° 0′ S.: long. 117° 0′ E.]. The rocks of these tholeiite suites are norites, tholeiites, and quartz-dolerites, frequently containing micro-pegmatite, and a little hornblende.

The age relations of these rocks are generally indeterminate. Those in the Meekatharra district intrude the (?) Tertiary Oakover limestones (7); between Laverton and the South Australian border they are overlain by the Wilkinson Range series, which are presumed to be either late Mesozoic or Tertiary (22). Elsewhere their age is indefinite.

Gibb Maitland suggests (13, p.43) that the lavas "may be of Middle or Late Tertiary age, and belong to the same period as the volcanic rocks occurring in South Australia and Victoria."

The tholeiites of S.W. Western Australia, and the olivine-basalts of Victoria are comparable in other directions. Both have developed in areas remote in space and time from orogenic periods: both have intruded a sedimentary and granitic crust: and both are situated near the continental margin.

Why, then, are they so different? In Victoria the basaltic magma gave rise to a typical olivine-basalt-trachyte suite (9): in Western Australia it gave rise to tholeiites. Since the generally comparable situations of these two basalt provinces preclude the possibility of such differences arising from assimilation, it seems necessary to postulate either that they resulted by very different types of differentiation (1), or that they were derived from initially different types of primary magma—olivine-basalt magma in the one instance, and tholeiite magma in the other: and that they therefore provide a local confirmation of the generalised hypothesis of W. Q. Kennedy (18).

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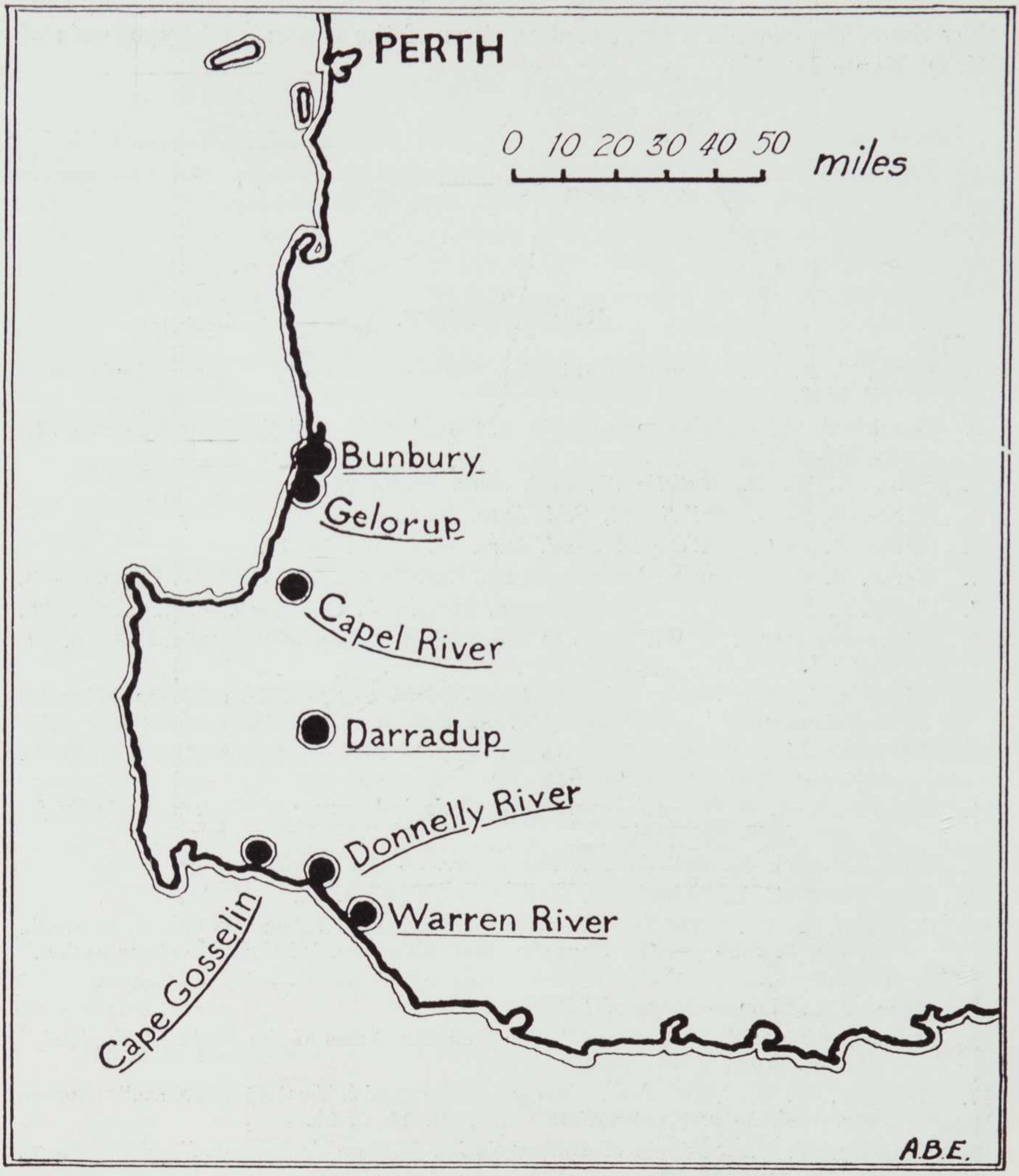

Fig. 1.—Locality Sketch Map.

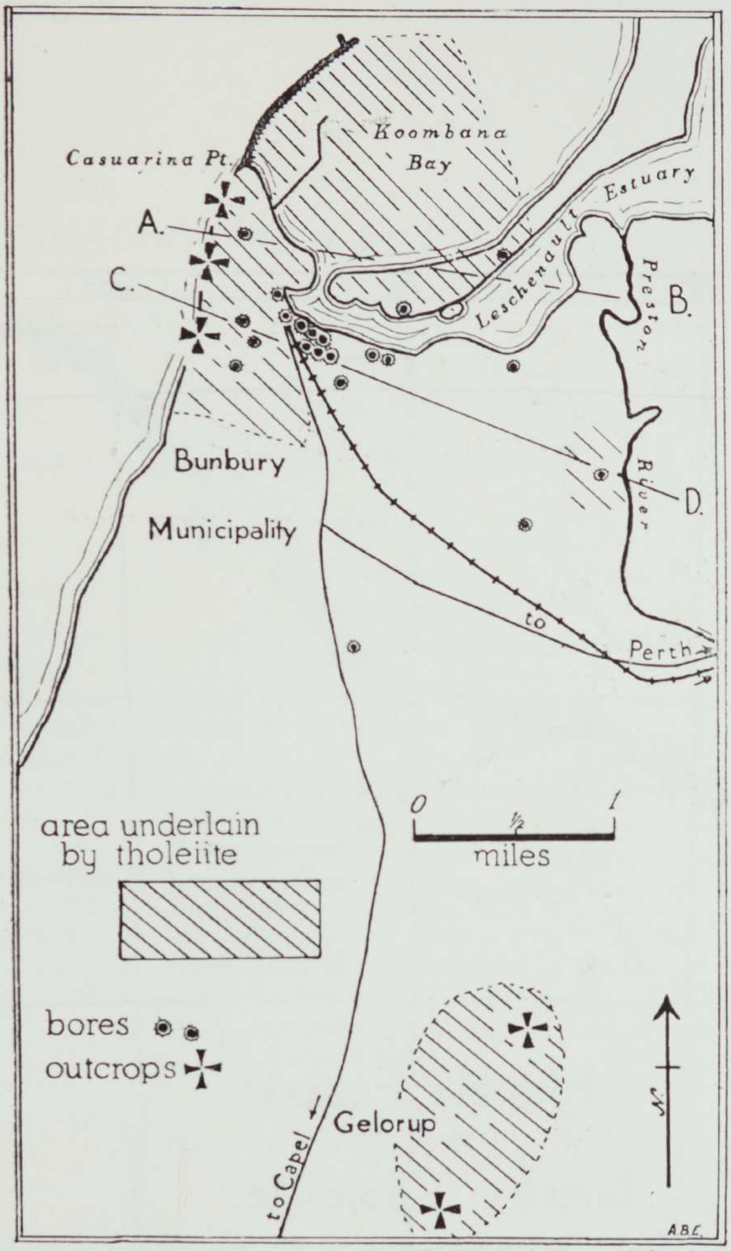

Fig. 2.—Sketch map of the Bunbury-Gelorup District, showing the known extent of tholeiite lavas and position of bore holes. (By the kindness of Dr. D. Carroll.)

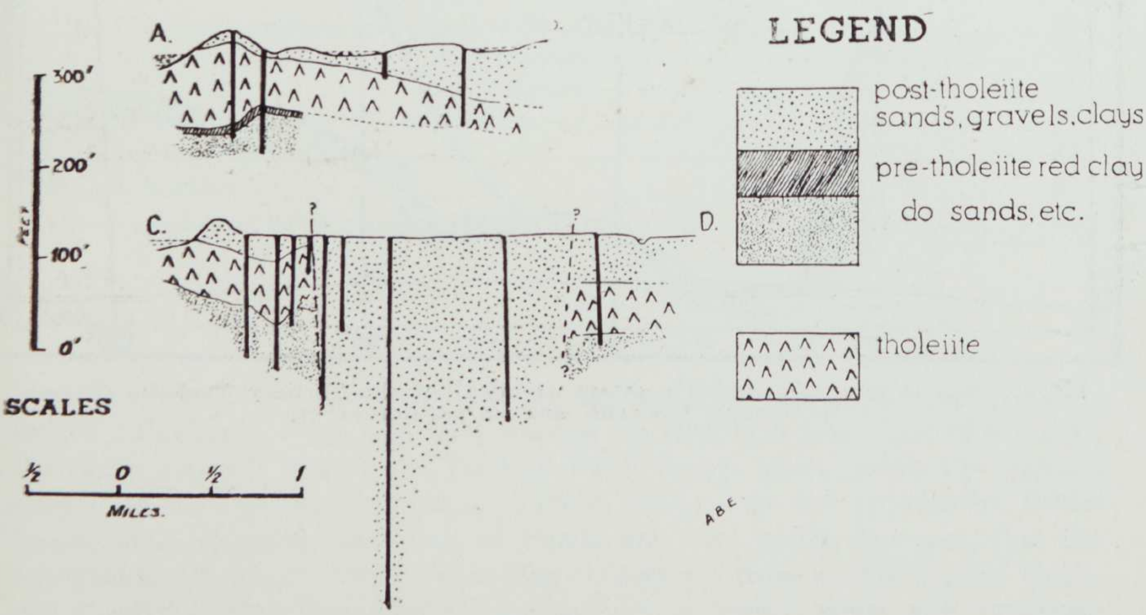

Fig. 3.
Geological sections along the lines A.B. and C.D. in Fig 2. Based upon boring records. (By the kindness of Dr. D. Carroll.)

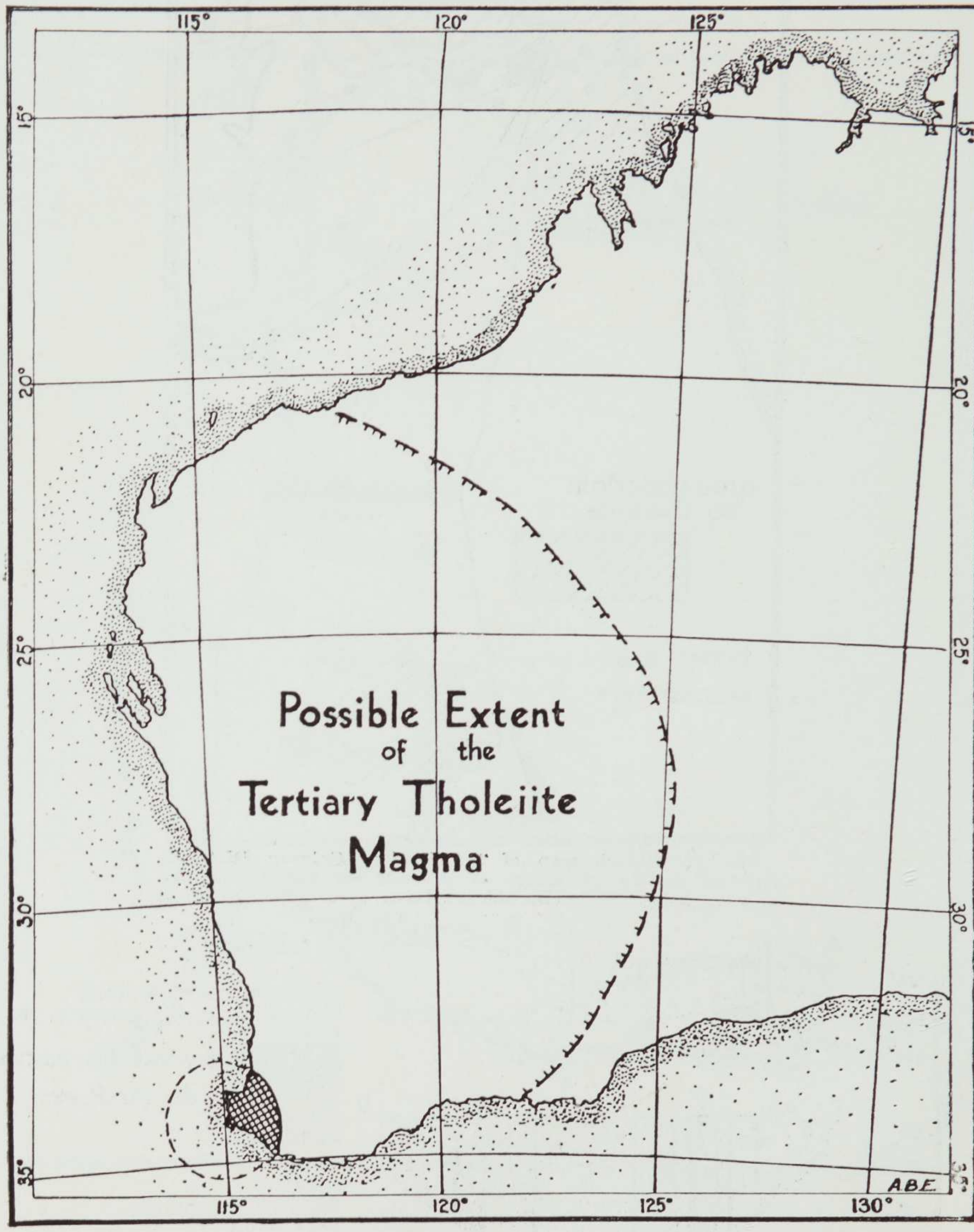

Fig 4.—Map showing the probable extent (shaded) of the Tertiary Tholeiite Magma in Western Australia, and its possible extent.